An Analysis of Recent Advances in Solid Ink Printer Performance from a Print Head Perspective

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Abstract

The customer experience of offset solid ink printing systems relies to a large degree upon the performance of four primary components: the print head subsystem, the transfer and fusing (or "transfix") subsystem, the receiver media, and the ink itself. While each of these ingredients plays a crucial role in the performance of the device, over the years the technology within the print head subsystem has been shown unquestionably to drive the greatest increases in offset solid ink printer performance. The following paper begins with an overview of an offset solid ink printing device highlighting the key aspects of this technology. Following this introduction, focus shifts to the print head subsystem, advances in which form the nucleus of a technology set enabling greatly improved print quality at speeds significantly higher than prior color offset solid ink printers.

Key technology elements of the print head subsystem are discussed, including their impact on system performance in terms of throughput, print quality, cost, and reliability. An architectural description of the subsystem will be presented, contrasting it with those that have come before. Similarly, jetting behavior will be discussed, as will calibration methods for the performance of the subsystem. The paper concludes with a brief look forward to the future of solid ink print head technology.

Introduction

Over 20 products have been introduced to the market using Xerox solid ink technology since the early nineties. Originally developed and marketed by Tektronix, Inc., solid ink is a type of ink jet printing, employing a "hot melt" ink that is solid at room temperature and liquid at jetting temperature. The ink changes phase from solid for shipping and storage, to liquid for jetting, and back to solid as it comes in contact with the receiver media (paper or transparency film). The earliest machines jetted molten ink directly onto paper. In the mid-nineties Tektronix introduced a solid ink printer that jetted first onto an intermediate drum before transferring the image onto the receiver sheet. Current Xerox solid ink machines utilize this basic technology, referred to as "offset" solid ink printing, in an ever evolving state. It is through this process of evolutionary technology advancement that Xerox is constantly in the process of introducing new solid ink machines with improved performance and reliability at lower cost. This paper reviews, somewhat technically, the latest advances, and especially those related to the print head.

One of solid ink's strong points has always been its simplicity, just as with other ink jet technologies. Leveraged successfully, this simplicity has translated to excellent reliability at acceptable cost. Figure 1 illustrates the simplicity of the solid ink printing process via cutaway view of a machine currently on the market. Solid ink sticks are loaded into a hopper on top of the machine (notably free of any packaging or cartridges). The solid ink is then melted into a page-width print head, which jets the molten ink onto an intermediate drum. Once an entire image has been accumulated on the drum, it is transferred onto the receiver through a pressure nip, and the final page is either ejected into the output tray or re-routed back through the machine for auto-duplex. It truly is a very simple printing process – no OPCs, no dryers, not even any ink or toner cartridges to deal with. Of course, there are limitations of the technology that must be avoided, as with all technologies. And also as with all technologies, the trick is to determine the implementation by which to best maximize the strengths while minimizing the weaknesses.

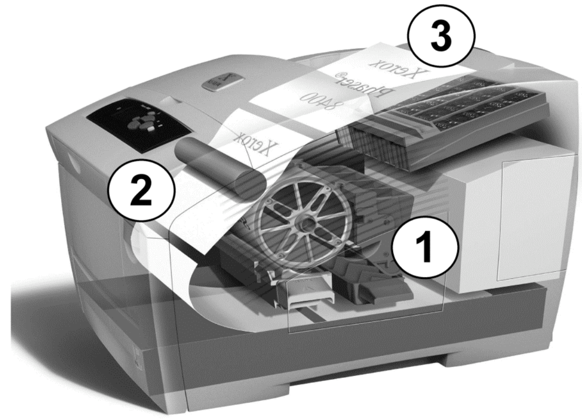


***Figure 1**. Xerox Phaser solid ink printer cutaway view.*
1) Print head subsystem; 2) Transfix subsystem; 3) Printed output.

Figure 2 shows the printing process in a little more detail. Take special note of the print head, which literally extends the width of a letter-size page. While the head is a true monolithic full-width array, it is not fully populated, meaning that the nozzle pitch of the head is lower than the dot pitch on the printed page. Specifically, print heads found within machines currently on the

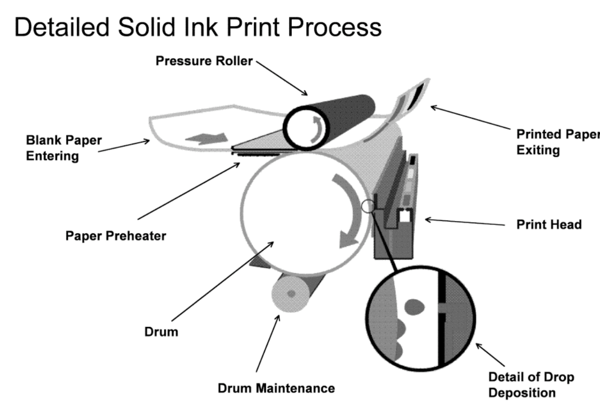


***Figure 2**. Solid ink print process critical components.*

market have nozzle densities of 150 jets per inch. Further, note that the head contains all four colors within one unit. This architecture leverages two of the fundamental inherent strengths of the basic print head design originally selected in the mid-eighties:

- ability to incorporate complex fluidic paths with relative ease, enabling tightly integrated 4-color print heads
- cost-effective scalability from small modular print heads to wide monolithic designs.

In the current product line, a head incorporating complex fluidic paths enables a tightly packed 4-color monolithic print head. The full-width head eliminates the need for a shuttling architecture. As will be revealed in greater detail with regard to the latest innovations in this technology, the above strengths are indeed two of the most significant keys to the future of solid ink printing.

Solid Ink Print Head Advances

Product-over-product, Xerox solid ink print head technology has advanced consistently. Utilizing an evolutionary development paradigm, current solid ink print heads linearly trace back to the first Tektronix designs of the mid-eighties. Over the years, performance, print quality, and reliability have increased steadily while cost per nozzle has dropped dramatically. Print head materials and basic layout have remained substantially similar to the first designs, but jet driver efficiency, packing density, and manufacturing process capability have all improved by leaps and bounds. The combination of these improvements applied to the aforementioned inherent strengths of the technology has enabled the advances in solid ink print heads discussed in this paper.

Sketched in Figure 3, the basic Xerox solid ink print head structure reveals a "bending mode" piezoelectric transducer (or PZT) coupled to a series of etched steel plates forming the internal fluid passageways. This "stack" of plates is referred to as the "jetstack." Molten ink is fed into the jetstack manifold via an ink reservoir, which is permanently attached to the jetstack. Precise flexure of the PZT creates a pumping effect used alternately to draw ink into the body chamber via the inlet and expel ink from the aperture via the outlet. The fluid path from the inlet, through the body, outlet, and aperture is known as the "single jet." Obviously, the geometry defining the entire fluid path and PZT actuator is of critical importance to print head performance, as is the PZT drive waveform, not to mention the physical properties of the ink and the jetstack itself. A detailed description of the intricacies of jetstack design is beyond the scope of this paper; however, the interested reader will find an excellent review of the fundamentals of solid ink jetstack design by Burr, et. al. [1].

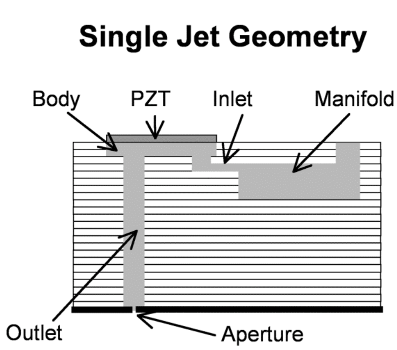


***Figure 3**. Simplified solid ink print head single jet geometry.*

Leveraging Jetstack Design Capability

The stack of stainless steel plates comprising the jetstack affords several advantages for solid ink printing. One of the most obvious is its potential for extremely high durability compared to silicon-based ink jet print heads, even at the elevated temperatures required for solid ink jetting. Another is its insensitivity to jetting fluid types. While adhesively bonded silicon and plastic print heads are relatively susceptible to chemical attack of many potential inks, the stainless steel construction of the solid ink print head jetstack is highly robust to most all ink compositions. Additionally, and of huge importance, the plate approach gives the fluid physicist tremendous flexibility in print head jet design.

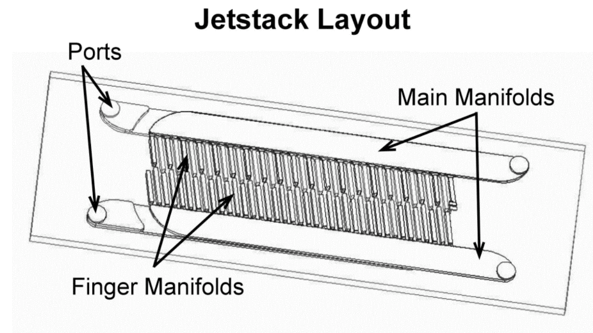


***Figure 4**. 4-color mirrored "comb-like" jetstack structure.*

All commercialized Xerox solid ink print heads are of 4-color design, meaning that all three process colors plus black are contained within one print head. While it is not uncommon to see 2-color ink jet modules, 4-color heads are much less common. A 2-color design can be visualized quite simply by picturing a repeating pattern of jets forming a comb-like structure with the second color the mirror image of the first, each comb fed by a unique color of ink (Figure 4). Such designs are prevalent especially in thermal ink jet. Building on the comb image, 4-color solid ink print heads may be visualized by stacking two 2-color comb structures on top of one another. It is the plate-based nature of the solid ink jetstack construction that enables this efficient packaging technique.

Since the introduction of the first print head having this general design in the nineties, several advances have been incorporated to improve packing density, mass flow rate capability, and print quality – all while reducing cost. One of the most substantial advances has been the introduction of finger manifolds (Figure 4). These smaller manifolds draw fluid from the main manifolds. Individual jets then draw from the finger manifolds. This concept of main and finger manifolds enables a 2-dimensional array of same-color jets, greatly increasing packing density, which enables immediate benefits to throughput performance and material usage efficiency.

Figure 5 reveals a CAD illustration of the fluid paths within the latest solid ink print head design, a 4-color print head having a 300 jet per inch packing density. Note the combination of overlain main manifolds and interwoven finger manifolds. The upper image views the body side of the jetstack, illustrating the mirrored structure, the finger manifolds (1), and the interleaved bodies of different colors (2 and 3). The lower image views the aperture side of the jetstack, where the jets can be seen drawing from the finger manifolds (4 and 5), with the fingers being fed by the main manifolds (6).

Indeed, the latest solid ink print head layouts are complex, which, it should be obvious, could only have come to be through the painstaking evolution of a sound initial design. It should now also be obvious that this structure does well to take advantage of the inherent strengths of the etched plate-based construction of these heads. Even without pushing too greatly the bounds of the manufacturing process, these 300 jet per inch print heads readily operate at frequencies above 40kHz all day long, at temperatures above 100°C, ejecting drops on the order of 20 nanograms (or roughly 20 picoliters), with a high duty cycle 5 year life.

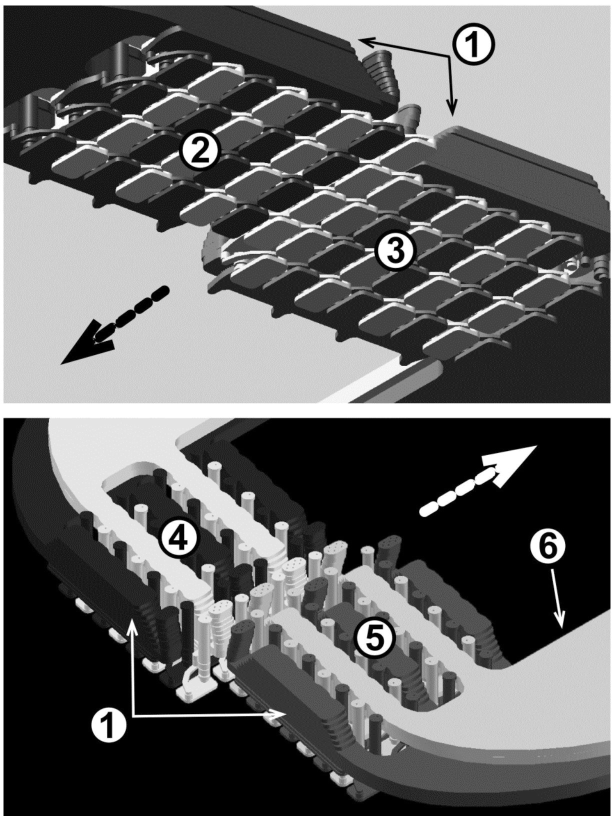


__Figure 5__. CAD model of 4-color print head fluid paths. 1) "Finger" manifolds; 2) body-side view of two colors interleaved; 3) two other colors interleaved; 4) aperture-side view of two colors interleaved; 5) two other colors interleaved; 6) "Main" manifolds. Note: in actual print head, jet geometry columns repeat the full length of the head, as indicated by the arrows.

Leveraging Jetstack Materials Capability

In addition to the flexibility to create complex features and fluid pathways, the etched stainless steel construction of these print heads makes readily possible scaling of the technology from one application or market to another. Truly, these print head designs can be scaled to comprise more jets or fewer, more length or less, and multiple or single colors. As has been proven recently, it is possible to scale silicon-based print heads [2], but so far only by aligning and gluing fewer or more complete modules onto a common reservoir. While in this regard their materials and processes limit these silicon-based heads, solid ink print heads enjoy great flexibility. In fact, the first solid ink print heads were about 2" in length, having been designed for shuttling-type architectures still commonly employed by many home ink jet printers today. It was not until the advent of the offset solid ink print process in the mid-nineties that the first full-width head came to be. Architects of this product took advantage of solid ink print head technology's capability to scale to greater lengths in order to remove the requirement for shuttling. This basic architecture continues to evolve, doing well in the color office printing market to this day.

What is right for one market or application may not be right for another, hence the advantage of simplified and efficient scalability. For example, full-width heads do make a great deal of sense, but as packing densities increase, the cost of a failed jet increases as well – especially for these print heads, which unlike silicon-based heads are intended to possess the reliability to last the lifetime of the printing device. The impact on reliability cost of a failed jet scales with the number of jets per head, as does scrap cost in manufacturing. Therefore, it is extremely valuable to have the ability to readily scale the print head to optimize cost, performance, and system complexity trade-offs.

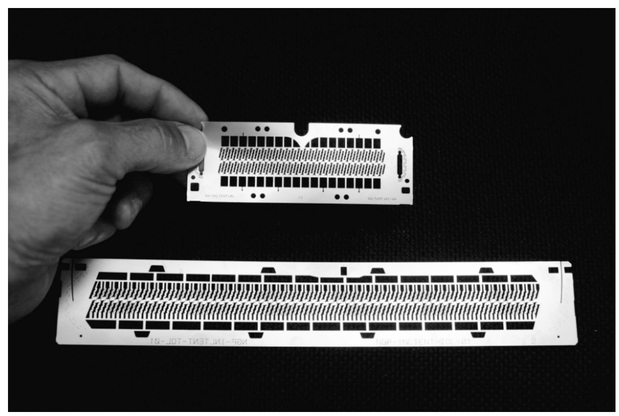


__Figure 6__. Modular (upper) and "full-width" (lower) print head plates, illustrating the continuously scalable nature of this technology.

Figure 6 presents an example of two print head jetstack plates from designs that are very similar from a fluidic standpoint, but very different in their intended application. While the lower plate is destined for an A4-market office color print head, the upper plate is destined for a modular print head better suited to higher-end multiple print head systems or industrial marking applications.

Application of Solid Ink Print Head Advances

Given these scalable advanced fluidic designs, development direction becomes a matter of selecting the application or applications that would provide the greatest return on the development investment. Testament to the true scalability of this technology, Xerox has been co-developing both full-width and modular versions of its print heads for more than 10 years. The primary application of the full-width head is, of course, the A4 color printer/MFP market. Secondary but fully realized applications of this print head include wide format printing, solid modeling, and industrial marking. With over a dozen A4 color printer models introduced in the last 10 years, there is no question that the bread-and-butter print head for Xerox has been of the full-width variety for quite some time. Meanwhile, as the full-width head has been enjoying good success in the market, an advanced modular version has been under development. Figure 7 reveals this modular print head.

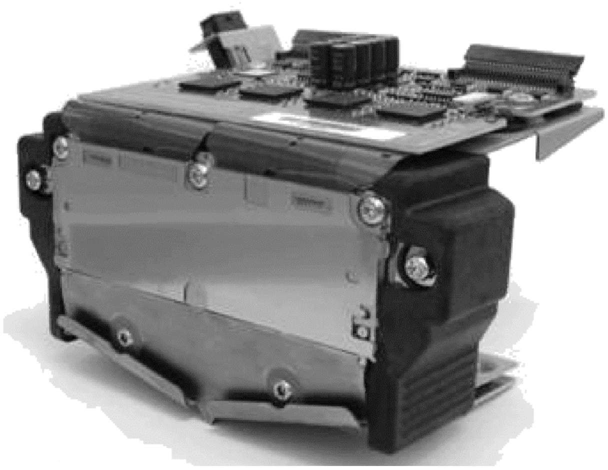
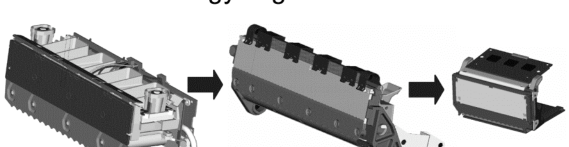


***Figure 7**. Modular solid ink print head, with approximately 3" active array.*

The modular print head presents an interesting contrast to the full-width head. Although it shares its technology set with the full-width head, because it is optimized to meet a very different set of objectives, it differs in many details from its wider sibling. Figure 8 contrasts these two heads according to several specifications. While the two greatest differences between the heads are clearly their widths and jet densities, subtle differences ripple through their specs. As has been previously discussed [1, 3], smaller single jet features generally translate to higher operating frequencies and smaller drop masses (or volumes), so it should come as no surprise that the modular head, at twice the packing density, operates at a higher frequency and ejects a smaller drop. What is more surprising, however, is that while the packing density has increased by a factor of two, drop mass has only decreased by a little over 10 percent. This is an important aspect for a head that has been optimized for high quality printing at high throughput speeds.

Print Head Technology Migration



	2002	2005	2008
Jet Density (jets/inch)	55	150	300
Basic Design	Pagewide	Pagewide	Modular
Jet Count (Head / System)	448 / 448	1236 / 1236	880 / 3520
Drop Mass (ng)	40 / 25	25	22
Operating Frequency	36	36	43
Ink Load	Drip	Drip	Pressure
Purge (Maintenance)	Vacuum	Pressure	Pressure
Purge (Maintenance)	Vacuum	Pressure	Pressure

***Figure 8**. Print head technology migration over time, highlighting the evolution of the full-width head and the advances of the modular head.*

Multi-head Solid Ink Printing Systems

Another point highlighted by Figure 8 is the important but obvious performance gain achieved by adding multiple print heads to a printing system. The full-width head is clearly designed for use as the single head in a printer, as it extends all four colors across the full width of a printed page. The modular head could be used in a single-head 4-color printing system, for example in an industrial marking or transactional/promotional application, but to take full advantage of its modularity, systems comprised of multiple print heads are really the best fit.

The CAD model of Figure 9 illustrates a multi-head solid ink printing system with four modular print heads situated around a drum. This example would have 3,520 jets covering an 11.75" print width. Because these print heads are designed for a five year life at full duty cycle, while there is no physical reason such a design couldn't be accomplished with a single extended length print head, manufacturing yield and warranty cost concerns assure a modular head is a more prudent choice – replacing a fraction of the jets rather than all 3,520 in case of a clogged aperture or two sure is a strong argument for modularity.

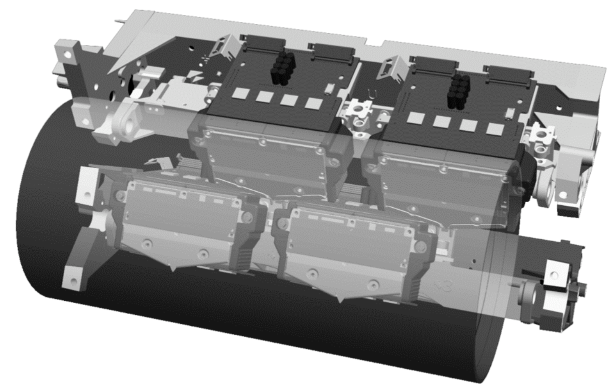


***Figure 9**. CAD model of modular print heads aligned around a drum (translucent for illustration purposes).*

Indeed, a strong argument is required to outweigh the simplicity offered by a single head, non-shuttling system, as in the solid ink printers currently on the market. The complexity of aligning multiple print heads relative to one another is a daunting task in and of itself, let alone calibrating the tone reproduction characteristics of each head to match its neighbor(s). While the head-to-head alignment requirements, on the order of 20μm, come as no surprise, the degree of head-to-head tone reproduction calibration may not be so expected. One of the strongest selling points of solid ink printing has always been its tone reproduction fidelity and consistency, and in single-head systems this is absolutely true. It must be kept in mind, though, that in most situations, there is no reference standard in a single head system – certainly not as there is in a multi-head system. Side-by-side comparisons of one head to another are inevitable in multi-head systems – occurring with nearly every print – effectively tightening the performance specifications of all the heads in a system relative to one another. The additional tolerances placed on the performance of each print head in a system are substantial to say the least, and maintaining these tolerances satisfactorily is surely one of the greatest difficulties in the development of multi-head solid ink printing systems. A complete discussion of all the aspects of managing head-to-head performance is indeed a topic worthy of an entire research paper, if not a series of papers. Needless to say, such a discussion is beyond the scope of this piece, but one example may do well to give the reader a flavor of the issues at hand, and the means by which they may be solved.

Solid ink printing has always been known for its vibrant colors and smooth optical density gradients [4], so the expectation of a multi-head system is quite high. In terms of print head specifications, it was experimentally determined and subsequently verified that head-to-head drop mass must be controlled to about 0.5 nanograms (ng) at all dither levels, for all colors, in order to meet customer-level head-to-head uniformity expectations. For a frame of reference, the single-head system drop mass specification range is on the order of a few nanograms depending on the dither level and color. Interestingly, this is a relative specification for each set of heads in a multi-head system. Not all heads produced have to be kept to within a super tight specification, but each set of heads within a system must match one another quite tightly.

Fortunately, there is great control available in driving a solid ink print head by nature of the technology. By making subtle changes to the drive waveform, print head jetting performance may be altered quite substantially. This characteristic is well known and documented [5, 6]. Figure 10 illustrates the basic drive waveform for a solid ink print head. Repeating at 43kHz, the length of the waveform is only about 23msec, and the height is about 50V peak-to-peak. Changes made at the microsecond level to waveform timing and voltage can alter jetting performance attributes, such as drop mass, quite significantly [3]. Applying subtle changes to the waveform driving jets both within head and head-to-head in a carefully controlled and monitored manner goes a long way toward calibrating head-to-head optical density uniformity.

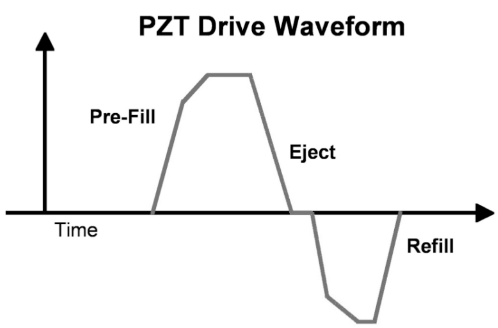


Figure 10. Simplified PZT Drive Waveform Example.

Figure 11 shows graphically the effect of waveform adjustment on head-to-head drop mass variation for a 4-head solid ink printing system. Each graph plots drop mass versus firing frequency for two conditions. "Partial frequency" printing for such a drop-on-demand ink jet technology refers to light optical density dithered areas; "full frequency" refers to solid fills. While it is common practice to calibrate print head full frequency drop mass via waveform adjustment in manufacturing, such is not the case for partial frequency drop mass. The upper graph of Figure 11 reveals the result of such a manufacturing strategy applied to a 4-head system, with nicely controlled full frequency drop mass and woefully inadequate partial frequency drop mass uniformity. While such an issue would go completely undetected in a single-

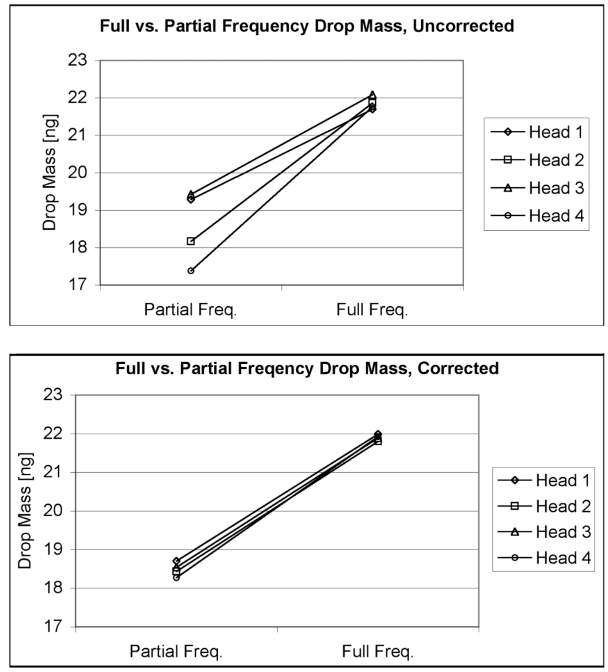


***Figure 11**. Drop mass vs. frequency for both uncorrected and corrected multi-head printing systems..*

head system, a multi-head system would possess unacceptable non-uniformity across a printed page. In searching for a solution to this critical issue, over the development of the modular print head, it was found that through the use of a very highly evolved waveform control scheme, it is possible to control both full frequency and partial frequency drop mass somewhat independently. The lower plot of Figure 11 presents the result of such waveform control applied to the print heads in this system, whereby both full and partial frequency drop masses meet the customer-level requirement of 0.5ng variation head-to-head.

As an aside, the observant reader will notice the fact that with this advanced print head design, drop mass is lower at partial frequencies than at higher frequencies. This trait is highly

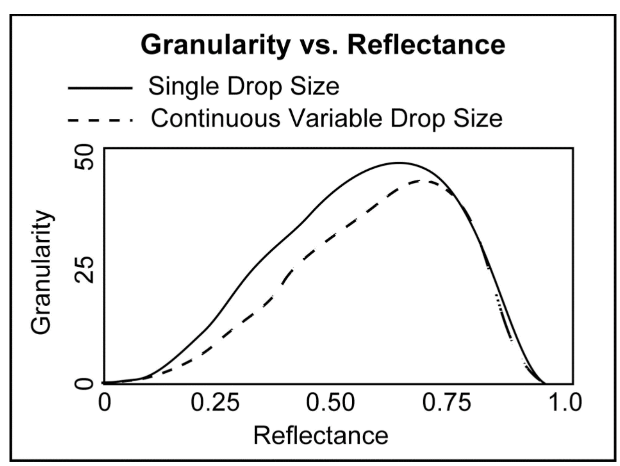
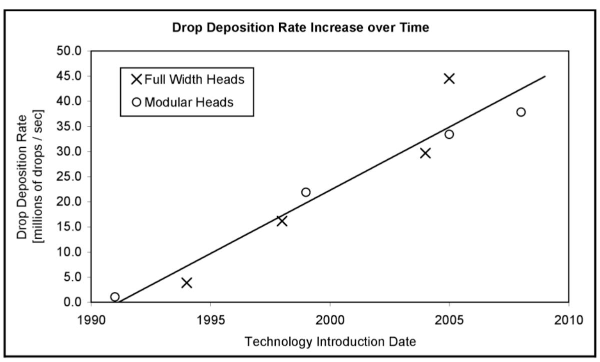


***Figure 12**. Granularity vs. Reflectance for single drop size and continuously variable drop size print modes. An explanation of the granularity metric is given in the literature [8].*

desirable and comes as no accident. Because graininess in solid ink printing is largely dictated by drop mass in light area fills and mid-tones, the benefit of this attribute is a reduction in graininess without compromising throughput (Figure 12). Throughout the course of solid ink print head technology development, different schemes have been employed to mimic this effect, with the most successful to date being the dynamic drop size switching print mode first productized several years ago [3, 7]. This print mode is however somewhat complicated and therefore does have real cost and implementation issues associated with it, so to have this behavior built-in to the head itself is quite a substantial benefit.

Conclusion

Over the two decades since its introduction to the marketplace, solid ink technology has continued to advance at an impressive rate. To date, these advances have resulted most apparently in a successful line of office color printers and MFPs. As these mainline products have been under development, for the past 10 years, a modular version of the solid ink print head has also been in the works. Figure 13 illustrates solid ink's technical advances over time via two key performance metrics for both of these print head platforms, showing that both data rate and mass flow rate continue to increase linearly. Additionally, the cost per jet of solid ink print head technology is aggressively trending downward, following a trend analogous to Moore's Law for solid state electronics (Figure 14). The advances in solid ink print head technology presented in this paper exemplify these trends of linearly increasing performance, aggressively decreasing cost per jet, and the migration of the technology into new markets and applications in the near future.



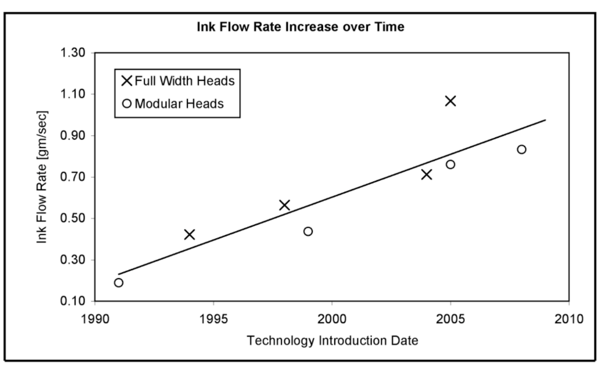


Figure 13. Solid Ink Print Head drop deposition performance over time, both in terms of data rate and mass flow rate.

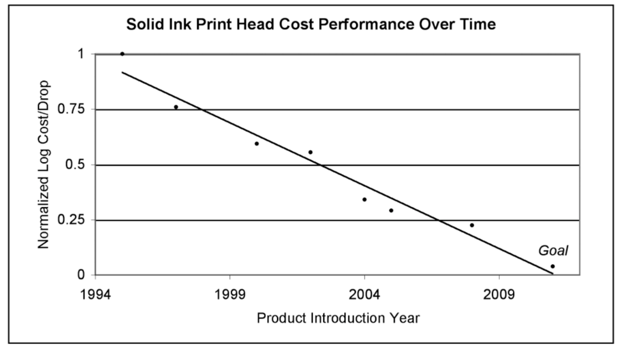


***Figure 14**. Solid Ink Print Head cost performance over time, following a trend analogous to Moore's Law for solid state electronics. Note: cost per drop calculated as the base 10 log of print head cost divided by the drop deposition rate, normalized by the cost of the first full-width solid ink print head.*

Acknowledgements

The advances in solid ink printing summarized in this paper have been brought to bear due to the efforts of a surprisingly small group of exceptional people over the years. A core group of maverick engineers, scientists, and technicians from Wilsonville, Oregon deserve special thanks, as do our friends from the Xerox Innovation Group of Webster, New York. Finally, without the vision of Ron Burr, the support of Rick Schmactenberg and Don Titterington, and the encouragement of Rick Dastin, the modular solid ink print head would in all likelihood not exist today.

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